

Pre-Flight Testing of Spaceborne GPS Receivers Using a GPS Constellation Simulator

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Biography

Semion Kizhner, an aerospace engineer with the National Aeronautics and Space Administration at the Goddard Space Flight Center, participated in the development of the Space Shuttle launched Hitchhiker carrier and payloads such as the Robot Operated Materials Processing System (ROMPS). He was responsible for establishing the GPS test facility at Goddard and supported GPS simulations for a dozen space projects, such as the OrbView-2 and SAC-A spacecraft. He graduated from Johns Hopkins University with an MS degree in computer science.

Edward Davis, an aerospace engineer with the National Aeronautics and Space Administration at the Goddard Space Flight Center, participated in the integration of the Spacehab Universal Communications System GPS experiments in the Space Shuttle and spacecraft such as AMSAT and SAC-A. He graduated from Salisbury State University with a BS degree in mathematics.

Roberto Alonso, an aerospace engineer with the Argentine Space Agency, is the Principal Investigator of the SAC-A GPS experiment. He graduated from the National Technological University (UTN) in Argentina with a BS degree in mechanical engineering and conducted post graduate studies in aerospace engineering at UTN.

Abstract

The NASA Goddard Space Flight Center (GSFC) Global Positioning System (GPS) applications test facility has been established within the GSFC Guidance Navigation and Control Center. The GPS test facility is currently housing the Global Simulation Systems Inc. (GSSI) STR2760 GPS satellite 40-channel attitude simulator and a STR4760 12-channel navigation simulator. The facility also contains a few other resources such as an atomic time standard test bed, a rooftop antenna platform and a radome. It provides a new capability for high dynamics GPS simulations of space flight that is unique within the

aerospace community. The GPS facility provides a critical element for the development and testing of GPS based technologies i.e. position, attitude and precise time determination used on-board a spacecraft, suborbital rocket or balloon. The GPS simulator system is configured in a transportable rack and is available for GPS component development as well as for component, spacecraft subsystem and system level testing at spacecraft integration and test sites. The GPS facility has been operational since early 1996 and has been utilized by space flight projects carrying GPS experiments, such as the OrbView-2 and the Argentine SAC-A spacecrafts. The SAC-A pre-flight test data obtained by using the STR2760 simulator and the comparison with preliminary analysis of the GPS data from SAC-A telemetry are summarized. This paper describes pre-flight tests and simulations used to support a unique spaceborne GPS experiment. The GPS experiment mission objectives and the test program are described, as well as the GPS test facility configuration needed to verify experiment feasibility. Some operational and critical issues inherent in GPS receiver pre-flight tests and simulations using this GPS simulator, and test methodology are described. Simulation and flight data are presented. A complete program of pre-flight testing of spaceborne GPS receivers using a GPS constellation simulator is detailed.

Introduction

Pre-flight testing of spaceborne GPS receivers is one of the primary functions of the Goddard GPS Test Facility (GGTF). The testing of receivers for use in spaceflight presents various challenges to the test engineers. Simulator systems are primarily designed, quite naturally, to test out receivers for terrestrial or aircraft applications. A typical Earth orbiting satellite would use a different set of body coordinate definitions than Earth-bound applications. This must be addressed when building simulations.

Spacecraft which will be using GPS technology also have various pointing requirements. An Earth pointing

spacecraft would be the simplest case for GPS space applications in that the antenna(s) would always be zenith pointing. Earth pointing spacecraft which will be flying GPS receivers in the near future include ICESat and Vegetation Canopy Lidar (VCL). The receivers for these two projects are currently being tested at the GGTF. Non-Earth pointers such as the Space Station and the Crew Return Vehicle will also be flying receivers whose flight algorithms have been developed and tested at the GGTF. Spinning spacecraft will also be flying receivers in the future and present another level of complexity in the design and testing of GPS receiver technology.

This paper discusses the GSFC experience with the first Satellite Aplicaciones Cientificas (SAC) spacecraft GPS experiment testing. The SAC-A spacecraft was to be flown in these three pointing regimes and thus presented the opportunity to test and fly a GPS receiver on a single spacecraft for various pointing modes.

SAC-A GPS experiment overview

The SAC-A was the first Argentinean spacecraft launched from the Space Shuttle into low Earth orbit on December 13, 1998. The spacecraft was a NASA Hitchhiker payload. The Hitchhiker was mounted in the Shuttle Bay and SAC-A was integrated into a Hitchhiker canister, and launched using the canister's ejection mechanism. After ejection the spacecraft is in a typical Shuttle orbit with altitude of 370.62 km and 51.6 degrees inclination. SAC-A is carrying a GPS experiment comprised of a 1 Hz GPS receiver called Tans Vector (trademark of Trimble Navigation Ltd), a GPS antenna array of four antenna-preamplifier units and associated harness. The receiver and the antennas are commercial products for terrestrial applications and the receiver was modified by NASA for space flight [1]. This GPS experiment is a complete, autonomous position, attitude and time determination system that was developed within the SAC-A International Space Project by NASA and the Argentinean Space Agency (CONAE). The on-board GPS experiment enables the SAC-A spacecraft position, attitude, and precise time determination for only limited time segments of the orbit. These segments depend on the SAC-A spacecraft orbital position, GPS antenna array boresight pointing, the GPS space vehicles (SVs) visibility and their Radio Frequency (RF) signal power levels as observed from the SAC-A spacecraft, as well as the receiver firmware initialization. At such times the above variables combine to allow the receiver position and attitude solutions. The Tans Vector was upgraded chiefly for a low Earth orbit and for a spacecraft whose GPS antenna array has a local zenith orientation.

SAC-A is a Sun pointing spacecraft and its solar array is the power source for nominal operations. The spacecraft GPS antennas' boresight vectors are parallel and antenna base plane is perpendicular to the solar array plane.

Therefore the GPS antenna array boresight vector will rarely point towards the near local zenith. In addition, the receiver has a fewer number of channels than the number of GPS space vehicles visible to the user spacecraft and a selection of GPS satellites becomes necessary. This presents, as was anticipated by the SAC-A spacecraft designers, a constraint and challenge in realizing the SAC-A GPS experiment's potential, as well as an opportunity to evaluate experiment performance under such constraints in space. Some other missions, like the EO-1 platform and the International Space Station, have GPS antenna configurations with similar constraints.

SAC-A GPS experiment objectives

The SAC-A GPS experiment mission objectives were described by the Argentine project team in [6] and are as follows:

- a) Test a GPS receiver in a long duration mission. The expected lifetime of the SAC-A spacecraft is about 6 months. This provides for long term testing of a low cost commercial GPS receiver. The spacecraft has alternative sensors such as a triaxial magnetometer (TAM) and coarse Sun sensors to verify and validate the GPS experiment attitude performance.
- b) Develop and test GPS flight operational procedures. The new generation of spacecraft may carry GPS sensors as a standard sensor. Therefore, it is important to test all the sequences of necessary procedures to implement missions in which this is possible. The SAC-A spacecraft is an adequate platform to carry out all these following procedures:
 - Implement software simulations of the GPS sensor in the mission profile.
 - Develop spacecraft onboard software to integrate GPS sensor to the Attitude Control System.
 - Test and calibrate procedures to identify and/or correct possible errors.
 - Integrate the GPS hardware to the spacecraft.
 - Analyze flight data.
- c) Test a GPS sensor usage on a spinning spacecraft. This spacecraft has the capability to be spun at different rates to provide an adequate scenario to test the GPS experiment performance, specifically in terms of the fast switching from one GPS satellite to another.
- d) Test a GPS sensor on a non Earth oriented spacecraft. This particular mission will also test the use of the GPS signals when the spacecraft attitude is non Earth pointing. The visibility and initial acquisition problem for SAC-A is more difficult than in Earth oriented spacecraft. SAC-A will implement maneuvers to place the antennas' axis as close as possible to the real zenith. In this scenario the GPS receiver is "locked" during a large portion of the orbit.

Figure 1 is the view of the SAC-A spacecraft. The four GPS antennas can be seen on top of the spacecraft with their axes parallel to the Si panel (solar arrays).

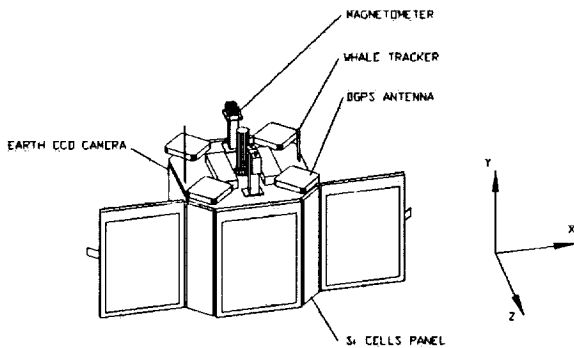


Figure 1. SAC-A spacecraft layout

1.0 SAC-A GPS experiment ground tests and simulations program

The goal of the SAC-A GPS experiment pre-flight testing was to check and evaluate the qualitative performance capabilities of the system in ground tests and simulations. To achieve this goal all flight components of the GPS experiment were tested at the GGTF before shipment to spacecraft integration in Argentina. The experiment was calibrated after spacecraft integration in Argentina [Section 1.5.2]. A set of pre-flight ground simulations using the STR2760/01 40-channel attitude simulator and a GPS receiver engineering unit were conducted by the Goddard GPS team at Goddard Space Flight Center in June - December of 1997. The simulation objectives were to implement test modes and cases that represent the worst orbital orientations of the GPS antenna array and to evaluate the qualitative performance using the Goddard GPS test facility constellation simulator. These cases were chosen to give the largest angle between the GPS antenna array boresight and the local zenith while maintaining the SAC-A spacecraft Sun pointing mode. All other variables were chosen to optimize the system performance in these orbits. Two required orbital orientation modes and nine mode variations were proposed for investigation. The test requirements were formulated by Dr. Glenn Lightsey/NASA GSFC [3] and Roberto Alonso/CONAE [4], [5].

1.1 GPS Simulation Modes

Two main ground simulation modes were implemented to achieve the simulation objectives. Within each mode a set of orbit cases were simulated to test different regimes of spacecraft operations.

Mode 1: In this mode the SAC-A spacecraft solar array is Sun oriented or the Yb axis [Figure 2] is pointing towards the Sun. The spacecraft rotates at one rotation per orbit (1 RPO) around the solar array boresight vector and in the direction of the spacecraft orbital motion to maintain a nearest local zenith for the GPS antenna array boresight vector throughout an orbit. Four orbits (cases) were simulated. The duration of each simulation was 5.5 hours.

Case 1: In this case the Sun is in the SAC-A orbital plane and the spacecraft is not rotating.

Case 2: In this case the Sun is 0 degrees above the Earth equatorial plane and the spacecraft is rotating at 1 RPO. The orbit plane is pseudo-perpendicular to the Earth-Sun vector (Sun vector) or the Sun vector projection on orbit plane is collinear with the simulated orbit minor axis.

Case 3: In this case the Sun is 23.5 degrees above the Earth equatorial plane and the spacecraft is rotating at 1 RPO. The orbit plane is pseudo-perpendicular to the Sun vector.

Case 4: In this case the Sun is 23.5 degrees below the Earth equatorial plane and the spacecraft is rotating at 1 RPO. The orbit plane is pseudo-perpendicular to the Sun vector.

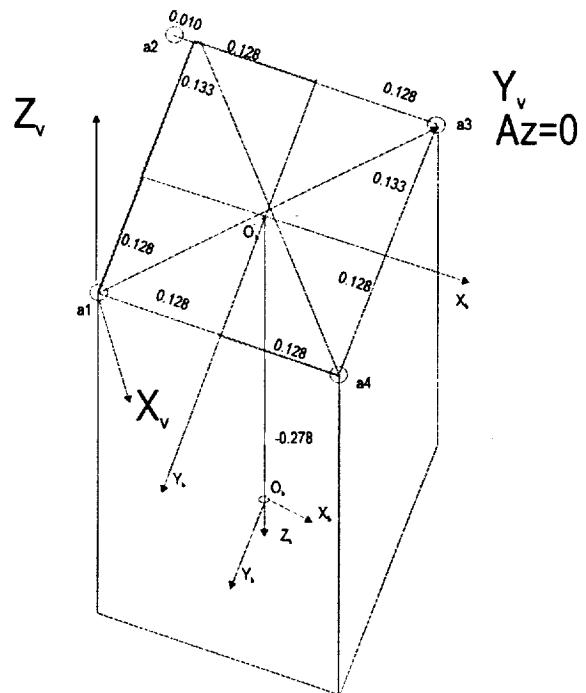


Figure 2. SAC-A body axes for simulations

Mode 2: In this simulation mode the SAC-A spacecraft is Earth oriented or the Zb axis [Figure 2] is pointing towards the Earth center. The spacecraft is spinning around the Zb axis (spinner spacecraft). The GPS antenna array boresight vector is local-zenith oriented. Four spin rates

were tested. The duration of each test scenario was 1 hour 30 minutes.

Case 5: 0 RPM (no rotation, spinner baseline test);

Case 6: 1 RPM or One Rotation Per Minute;

Cases 7, 8: 3 RPM and 4 RPM correspondingly.

For each of the above simulation cases a set of resulting data was produced. In each set of simulation results there is data representing truth and measured position as SAC-A spacecraft latitude, longitude, altitude, as well as attitude heading, roll and pitch.

1.2 GPS Simulations Configuration

Figure 3 represents the GPS test facility physical configuration used to verify the SAC-A GPS experiment feasibility and qualitative performance. This configuration comprises the following elements:

GPS simulator: The Goddard GPS test facility houses the GPS 40-channel attitude simulator STR2760/01 which replicates the On-Orbit Radio Frequency environment for the test receiver. The GPS receiver was connected to the simulator output spare RF ports. The receiver's control personal computer (PC) was also connected to the simulator workstation with a point-to-point simulator vendor network interface that allowed the simulation truth position and attitude data to be transferred to the PC.

GPS receiver: A spare Tans Vector engineering unit for space flight applications was configured as the SAC-A on-board GPS receiver and was controlled (commands and data handling, and data archiving) from the PC. The receiver's vendor ground control program was modified to simplify some operations for receiver aiding.

GPS PC: Ground telemetry monitoring and commands PC is running DOS and Windows, and the vendor's receiver command and telemetry software. The combined truth and measurement test data processing was done on a comparable PC using standard commercial analysis tools.

The spacecraft GPS antenna array relative geometry and four matched antenna gain patterns were modeled within the simulator work station.

Preamplifiers: Four preamplifiers of the same model as in the flight antenna amplifiers were used to connect the GPS simulator RF outputs to the receiver.

Harness: RF, power and data cables of the same model as used by SAC-A were used in the simulations.

Simulations configuration control: The entire simulation system configuration was fixed for the duration of the SAC-A simulations. This was made possible by using the simulator spare RF ports. It allowed two projects to use the simulator without hardware configuration changes when switching between two projects. It also assured the validity of a single long-duration simulator based Self-Survey [Section 1.5.2] for the duration of the test program.

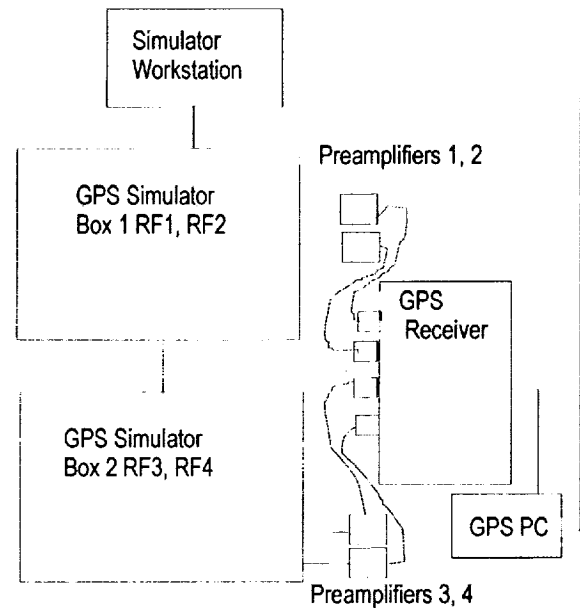


Figure 3. GPS Simulations Configuration

1.3 GPS Simulation Initialization

Correlation between the spacecraft-defined body frame and the simulator default frame is a critical issue. The simulator frame must be interpreted carefully such that there is a direct correlation between the simulator default frame and the spacecraft defined frame. The SAC-A spacecraft body axes frame selection for simulations is described below in Section 1.5.1

The GPS simulator RF output signal power levels are modeled within the simulator. This modeling must be tuned carefully to best match that which would be experienced by the receiver on orbit. Failure to address this issue would result in the invalidation of the test results.

Spacecraft initial orientation is a simulator input and its determination is subtle. The spacecraft Sun pointing requirement presented a challenge in defining the initial orientation between the spacecraft body axes frame (chosen for simulations by user) and the spacecraft reference frame used by simulator. The initial orientation can be determined intuitively for some specific choice of simulation orbits and dates at which the Sun-Earth positions are evident or by using stand-alone orbit analysis tools. The former was used in SAC-A simulations. A tool to determine the angles was developed later.

Simulator GPS satellite visibility modeling must be comparable to that of the receiver. The GPS SV visibilities and selection criteria on the simulator and receiver may be different. The simulator must be adjusted

through the definition of several variables such as obscuration angle or Earth tangent versus local horizontal obscurations in order to model the GPS constellation as it would be visible to the SV search algorithms within the receiver.

The dilution of precision selection modes on the simulator and receiver may be different and this issue must be properly addressed in a simulation program. The SAC-A receiver's preferable satellite selection mode is Highest Elevation which may not be available on simulator. The receiver's Highest Elevation mode mitigates a GPS signal obscuration by spacecraft structures and allows for SVs with higher power levels. This presents a problem of matching the sets of GPS satellites tracked by the receiver and simulated by the simulator. Attitude simulators may simulate satellites that have very low (negative) signal levels which are not detectable by the receiver.

The GPS facility attitude simulator configuration allows up to ten SVs on all four RF outputs. In addition, the attitude determination requires that the RF signals are simulated from the same set of GPS satellites making 10 the definitive upper limit. On orbit there are often more than 10 SVs visible to a GPS receiver and this becomes an issue of testing the receiver's ability to process signals from more than 10 GPS satellites.

Rotational maneuvers required for SAC-A involved manual tuning of the simulated rotation maneuver rate. It was needed to approximate a spacecraft rotational rate close to a constant as much as possible. This SAC-A experience led directly to the development of procedures to automate the rate parameters selection.

1.4 GPS Receiver Start-up Parameters

The SV search algorithm in the SAC-A receiver is set to search for GPS satellites at the highest elevations. To do attitude determination with multiple antennas, the system must know the physical location of the antennas and the RF response from each when they are in flight conditions. A time consuming Self-Survey (SSVY) calibration activity is required to establish these values [1], [7]. The data obtained from the SSVY, which includes these geometrical baselines and electrical cable biases, is retained within the receiver and used in the calculation of attitude solutions. The SSVY may be replaced in the future by the receiver dynamic calibration.

The SAC-A has very small GPS antenna baselines (distances between antenna 1 and 2, 1 and 3, 1 and 4 or B1, B2, B3) and this diminishes the attitude accuracy. The Tans Vector nominal baseline is 1 meter or larger. The SAC-A B1 is close to 261 mm.

The definition of the spacecraft orbital elements in the receiver orbital frame and the orbital elements used to define the test scenarios on the simulator are different due to their different coordinate frames. The receiver orbital elements were determined by running a few small tests for each chosen long simulation and allowing the receiver to determine its orbit elements set in the cold start mode. The orbital elements were then downloaded by receiver command to a text file. The use of this data enabled the use of an ephemeris aided search algorithm to hasten the time to first fix.

The issues presented are inherent to operations of complex systems like a GPS simulator and a GPS receiver. All operational issues were successfully resolved for the SAC-A project.

1.5 GPS simulation critical issues

There are a few critical issues involved in a simulation using a GPS simulator. Each of the initialization issues described above require detailed analysis and unique solutions to ensure successful engineering tests. Two of these critical issues are highlighted here to illustrate the complexity of spaceborne GPS receiver validation. The first is the selection of the user spacecraft body axes frame and the other is the calibration of the GPS experiment sensor. Both issues involve the coordinate frames used in a simulation.

1.5.1 SAC-A body axes frame selection for the GPS simulator test scenarios.

In a GPS simulation scenario three coordinate frames centered at the user spacecraft are of interest:

- a) the local geographical frame North-East-Down (NED) in WGS-84, a traditional frame used by aircraft;
- b) the spacecraft reference frame $\{X_r, Y_r, Z_r\}$;
- c) the spacecraft body axes frame $\{O_b, X_b, Y_b, Z_b\}$ fixed to the spacecraft.

The first two frames are features of the simulation system in which the spacecraft reference frame can be selected as an input parameter from a few available choices. For a Sun pointing choice the frame's Y_r axis points towards the Sun throughout a simulation. For an Earth pointing choice the Z_r axis points towards the Earth. Once the choice is made this frame becomes with the NED frame an automatic feature of the simulation system. The spacecraft body axes frame $\{O_b, X_b, Y_b, Z_b\}$ for simulations is selected by the user [Section 1.1 Figure 2, dimensions are given in meters]. The spacecraft's initial orientation of $\{O_b, X_b, Y_b, Z_b\}$ in relation to $\{X_r, Y_r, Z_r\}$, is specified by the user as a simulation input. Once initialized the two frames orientation is fixed for the duration of a simulation unless additional spacecraft maneuvers are requested. The spacecraft initial orientation and the attitude maneuvers

during a simulation determine the GPS experiment performance for all its functions. The spacecraft simulated attitude is then defined as the orientation of $\{Ob, Xb, Yb, Zb\}$ in relation to NED, namely by three Euler angles of the spacecraft rotations around its body axes in order (Zb, Yb, Xb) or (3,2,1). These angles would orient the spacecraft from visualized axis-by-axis alignment of two frames at the attitude solution time to the proper orientation of $\{Ob, Xb, Yb, Zb\}$ with the spacecraft reference frame. A rotation is positive if it is clockwise as observed from frame origin looking towards the rotation axis positive direction.

The receiver attitude is defined as the orientation of its platform frame $\{Xv, Yv, Zv\}$ in relation to the local geographic coordinate system East-North-Up (ENU).

The body axes frame selection for simulations is important for the simulated attitude and receiver measured attitude compatibility and to spare transformations in the measurement data processing. For the simulations with the attitude GPS simulator the SAC-A spacecraft body axes frame was chosen in a way that no frame transformations were necessary and the attitude reported by the receiver followed the truth attitude. The SAC-A spacecraft body axes frame chosen for simulations is depicted in Figure 2. The SAC-A GPS antenna mechanical centers in this frame were used for the antenna location inputs in the simulator and were an invariant for the Self-Survey using the GPS simulator and all simulations. Once the receiver completed the SSVY using the simulator RF signals it was initialized with the resulting SSVY data, including the SSVY determined offset azimuth angle. Then in all simulations the receiver measured attitude follows the simulator truth attitude.

1.5.2 Static Self-Survey using sky and the GPS simulator signals.

For ground GPS simulations a 6 hour Self-Survey was conducted using the attitude GPS simulator and the Tans Vector prototype of the SAC-A flight GPS receiver, and using Figure 2 GPS antenna array layout on the simulator. A static scenario with an arbitrary specified fixed geographical location (longitude, latitude, height in the frame implemented by the simulator) was used on the GPS simulator. This resulted in a self-survey output file on the Tans Vector system. This file describes the GPS antenna array baselines in the Tans Vector ENU frame that is used by the receiver and is centered at antenna a1 (Master). The file also contains the Azimuth offset (delta) angle or baseline B2 offset from North and the three differential line biases. During operations, when this delta angle is input to the receiver, the receiver will produce consistent attitude solutions (Heading, Elevation or roll, Pitch or bank), that are within a few degrees from the truth attitude displayed on the GPS simulator.

The difference between the simulator/receiver Self-Survey results and theoretical baselines (antenna coordinates input to the simulator) can be used to evaluate the correctness of the self-survey using the GPS simulator. The theoretical values of baselines B1, B2, B3 can be found from the given above antenna array coordinates in the body axes frame entered into the simulator. The measured baseline 1 length from the Self-Survey data is 261.9445 mm. The theoretical baseline 1 length is 261.1915 mm. The difference between the measured and theoretical baseline 1 is less than 1 mm. The same result holds for the remaining baselines 2 and 3 indicating that the self-survey using the GPS simulator was successful. The SSVY accuracy using the GPS simulator attests to the simulator and the receiver integrity and adequate attitude simulation accuracy.

At the spacecraft level, the flight Tans Vector receiver with the flight antenna array and cables mounted on the SAC-A also required calibration. This SSVY is needed for the spacecraft GPS experiment attitude subsystem initialization, and data obtained from this SSVY was flown on orbit. The spacecraft ground Self-Survey using sky signals is also used to check the antenna to receiver RF path integrities, which includes both the connection sequence at the GPS receiver RF input ports, and the electrical path continuity from each GPS antenna to the receiver. The SAC-A spacecraft 9-hour Self-Survey was completed by the NASA/CONAE team in Bariloche Argentina using the sky GPS signals.

1.6 Orbit simulations and test program implementation methodology

Numerous test cases were developed to test the GPS system for different orbital scenarios. In choosing a test case the right ascension, the scenario start date and time were the main variables. Orbits and spacecraft initial orientation for each case were implemented by selecting the simulation start date and time, orbit right ascension and spacecraft initial Sun-pointing orientation.

For the Sun pointing cases, the date was varied to ensure that the Sun line in relation to the orbital plane would be modeled over its entire range. These different Sun angle cases each presented unique constraints on the antenna boresight pointing. For the spinning spacecraft case the SAC-A was modeled as an Earth pointing vehicle with the spin axis toward nadir while the antenna boresight axes point toward zenith.

1.6.1 Sun oriented Mode 1 simulations

In mode 1 the SAC-A spacecraft is in Sun pointing and is rotating at 1 RPO. The duration of all test scenarios is 5 hours 30 minutes and spans more than 3 orbits [2].

Case 1

{test start date=March 21 1997, right ascension=0 degrees}, spacecraft initial orientation {180, 0, -90}, no rotation; Sun is in SAC-A and in any orbit plane with right ascension 0 at Vernal Equinox date. The GPS antenna array base is parallel to the spacecraft orbit plane.

Case 2

{test start date=March 21 1997, right ascension=+90 degrees}, spacecraft initial orientation {180, 0, 0}, 1 RPO around axis Yb, positive rotation at a rate of 0.00116 radians/second.

Case 3

{test start date=June 22 1997, right ascension=0 degrees}, spacecraft initial orientation {236.5, 0, 0}, 1 RPO around axis Yb, negative rotation at a rate of 0.00116 radians/second.

Case 4

{test start date=Dec 22 1997, right ascension=0 degrees}, spacecraft initial orientation {156.5, 0, 0}, 1 RPO around axis Yb, positive rotation at a rate of 0.00116 radians/second.

1.6.2 Spinner Mode 2 simulations

In mode 2 the SAC-A spacecraft is Earth pointing. The Zr, Zb axes are pointing towards the Earth. The spacecraft is spinning around the Zb axis (that is parallel to the GPS antenna array boresight vector) to investigate spin affects on attitude determination. These cases were implemented in scenarios of 1 hour 30 minutes duration or for 1 orbit.

Case 5

{test start date=March 21 1997, right ascension=0 degrees}, spacecraft initial orientation {0, 0, 0}, +0 RPM around axis Zb.

Case 6

{test start date=March 21 1997, right ascension=0 degrees}, spacecraft initial orientation {0, 0, 0}, +1 RPM around axis Zb.

Case 7

{test start date=March 21 1997, right ascension=0 degrees}, spacecraft initial orientation {0, 0, 0}, +3 RPM around axis Zb.

Case 8

{test start date=March 21 1997, right ascension=0 degrees}, spacecraft initial orientation {0, 0, 0}, +4 RPM around axis Zb.

2.0 Simulation Results

The SAC-A GPS experiment ground tests and typical simulation results are summarized below and a flight data

pattern from a single day of operations in orbit is presented.

2.1 Ground simulations data processing

summary

Ground simulations indicated that a Sun pointing and rotating spacecraft allowed the receiver to find position and attitude solutions in all cases of this mode for 30% or more of an orbit. The Earth oriented spinning spacecraft allowed the GPS receiver to find position and attitude solutions at up to three RPM. The GPS ground simulations demonstrated the SAC-A flight GPS experiment feasibility and potential in different regimes of operations - Sun pointing rotating mode, Earth oriented non-spinning mode and Earth oriented spinning mode. Figures 5 - 9, show representative graphs for position (latitude) and attitude (heading) obtained in ground simulations for the different regimes of spacecraft operations. The truth data is plotted as a thin line and measurement data as a brush line.

2.1.1 Sun pointing and rotating spacecraft regime of operations

Figure 5 and Figure 6 are two representative graphs for position (latitude) and attitude (heading) obtained from the Case 2 ground simulation scenario. The spacecraft is in Sun pointing mode and rotating at 1 RPO.

Figure 5 shows that the receiver was doing position fixes for about 30% of an orbit.

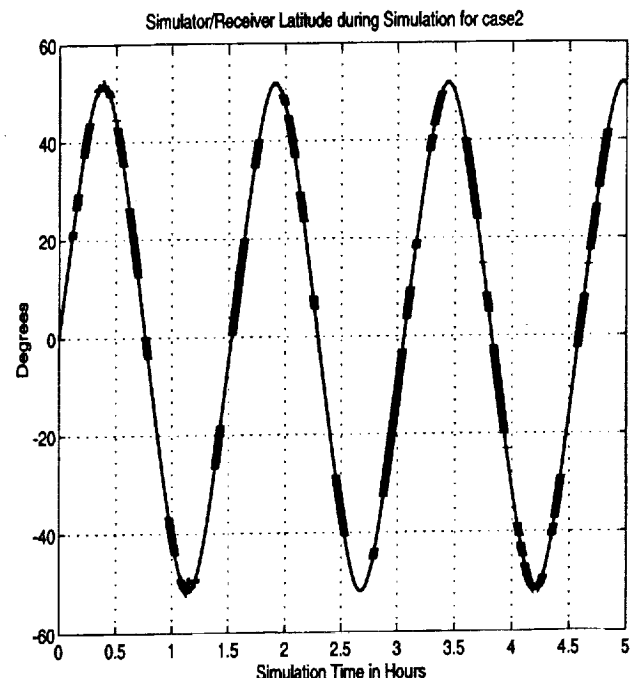


Figure 5. Case 2 Latitude/Time truth and measurement

Figure 6 similarly shows that attitude solutions were also obtained for about 30% of an orbit. As a point of interest in this plot, it can be seen that the spacecraft heading reported by the receiver began to diverge from the truth model between two and two and a half hours. This was due to the loss of a navigation solution during this time as seen in the previous plot which gradually corrupted the attitude accuracy within the receiver.

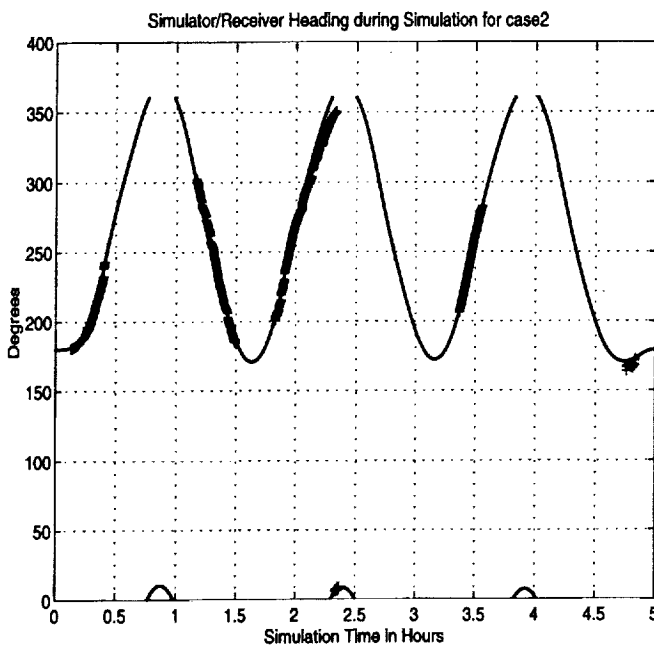


Figure 6. Case 2 Heading/Time truth and measurement

2.1.2 Earth pointing spacecraft regime of operations

Figure 7 shows consistent attitude solutions of the Earth oriented non-spinning spacecraft. In this particular case, the simulation was halted about forty-five minutes into the run as can be seen on the plot.

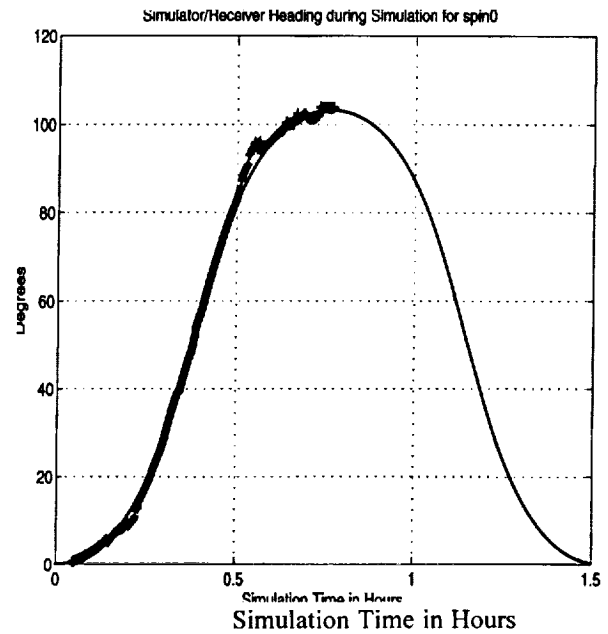


Figure 7. Case 5 Spin 0 Heading/Time truth and measurement

2.1.3 Earth pointing and spinning spacecraft regime of operations

On an Earth oriented spinning spacecraft, as observed in Figures 8 and 9, the GPS receiver was able to determine position and attitude at 1 RPM. The receiver could not determine attitude at rotation rates higher than 3 RPM.

Figure 8 shows that the navigation solution from the receiver during the one RPM spinning spacecraft case existed for a significant portion of the orbit.

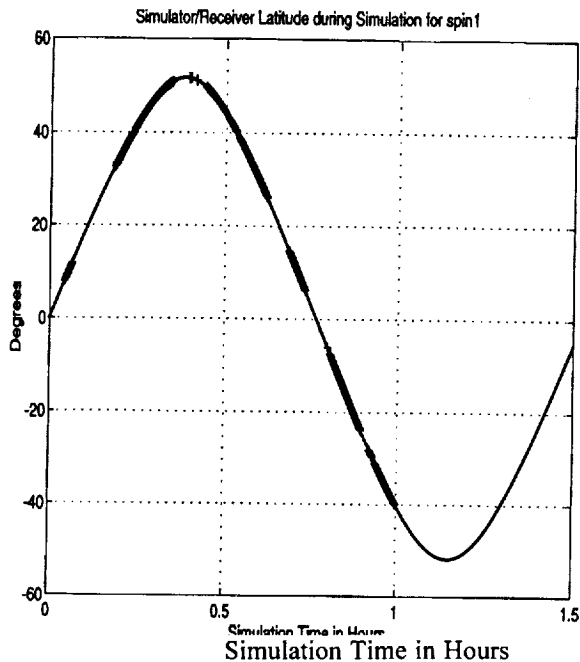


Figure 8. Spin 1 RPM Latitude/Time truth and measurement

Figure 9 shows the spacecraft heading during the one RPM spinning case. The darker portion of the plot shows the receiver successfully calculating attitude solutions for the first half hour of the test.

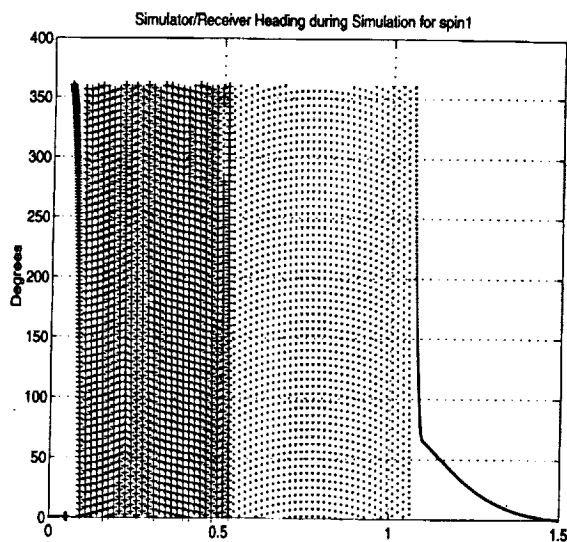


Figure 9. Spin 1 RPM Heading/Time truth and measurement

3. Flight Data Analysis

At the time of this writing, the SAC-A is nearing the completion of its expected mission. The GPS experiment has been extremely successful in demonstrating the use of GPS for various space flight regimes.

Figures 10 to 12 contain a pattern of flight data for a time segment when the GPS experiment was powered on. In this summary a sample of flight data collected on March 23, 1999 (close to Vernal Equinox simulation Case 2) is displayed. Figure 10 demonstrates that the spaceborne GPS receiver was successfully determining orbital position for a similar percentage of the orbit as predicted in Case 2.

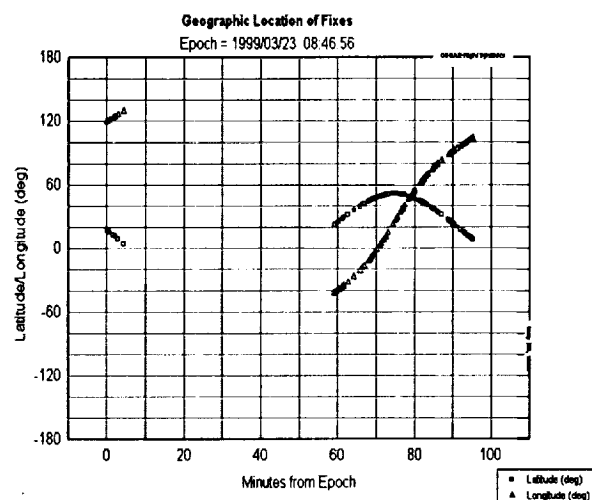


Figure 10. SAC-A flight position measurement

Figures 11 and 12 show typical errors in the position (in km) and velocity (in m/s) measurements from the GPS receiver on orbit.

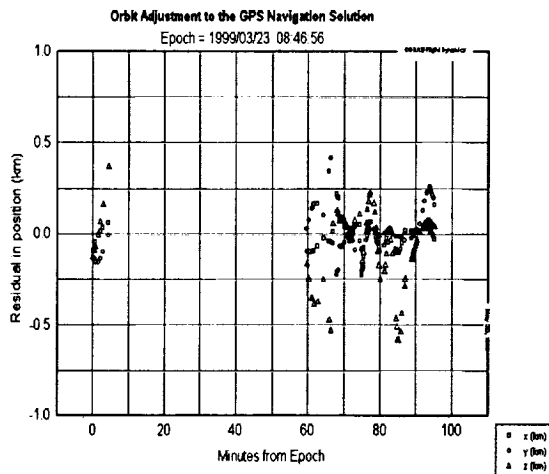


Figure 11. SAC-A GPS Navigation Error

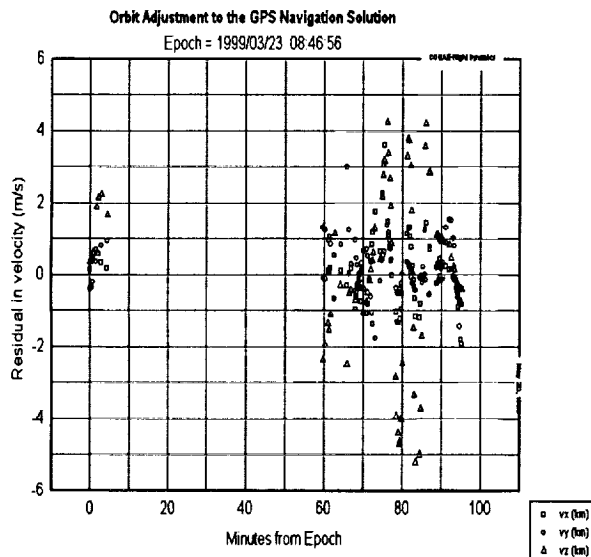


Figure 12. SAC-A GPS Velocity Error

Typically the errors between the attitude given by magnetometer or Sun sensor, and the attitude given by the GPS experiment, are 4 degrees.

As an example, the GPS experiment was ON between 8:45 to 10:29 UT of the 03/23/99.

Attitude fixes were between 10:08 - 10:25 UT of the 03/23/99.

A snapshot of GPS receiver on-orbit Y axis [Figure 1] attitude solutions in inertial frame is shown below.

| | | | |
|-----------|----------|----------|----------------|
| -0.003716 | 0.134790 | 0.990867 | @ 10 : 08 : 19 |
| -0.019470 | 0.148602 | 0.988706 | @ 10 : 08 : 34 |
| -0.026688 | 0.147161 | 0.988752 | @ 10 : 09 : 08 |
| -0.020882 | 0.143013 | 0.989500 | @ 10 : 10 : 11 |
| -0.014980 | 0.137507 | 0.990388 | @ 10 : 11 : 16 |
| -0.017244 | 0.136795 | 0.990449 | @ 10 : 12 : 05 |
| -0.011409 | 0.132601 | 0.991104 | @ 10 : 13 : 07 |
| -0.004730 | 0.118217 | 0.992977 | @ 10 : 14 : 11 |
| -0.000102 | 0.113618 | 0.993525 | @ 10 : 15 : 13 |
| -0.008184 | 0.114421 | 0.993399 | @ 10 : 16 : 02 |
| -0.011947 | 0.112529 | 0.993577 | @ 10 : 17 : 07 |
| -0.030667 | 0.131374 | 0.990859 | @ 10 : 18 : 12 |
| -0.034001 | 0.132940 | 0.990541 | @ 10 : 19 : 17 |
| -0.032205 | 0.128608 | 0.991173 | @ 10 : 20 : 04 |
| -0.033155 | 0.134714 | 0.990330 | @ 10 : 21 : 08 |
| -0.029883 | 0.151930 | 0.987940 | @ 10 : 22 : 12 |
| -0.020896 | 0.151713 | 0.988204 | @ 10 : 23 : 14 |
| -0.024234 | 0.153555 | 0.987843 | @ 10 : 24 : 02 |

The GPS experiment data for an intermediate time point can be interpolated from the above vectors and matched with a TAM measurement vector for a chosen time point.

Computed with the TAM sensor:

Y axis (momentum bias axis) was at 08:45

-0.002 0.069 0.998 relative to inertial frame.

Y axis (momentum bias axis) was at 10:25

-0.009 0.100 0.995 relative to inertial frame.

The TAM data for an intermediate time point can be interpolated from these two vectors.

The angle between the Y axes determined by TAM at 10:25:00 and the GPS experiment at 10:24:02 can be estimated from the two vectors' dot product and is 3.162 degrees.

Conclusions

The SAC-A GPS experiment pre-flight tests and simulations provided an insight into the experiment on-orbit capabilities. A final test report was produced that allowed the SAC-A control team to implement the spacecraft and the GPS experiment operational procedures. The GPS experiment on-board the SAC-A spacecraft performs as designed and preliminary results from its telemetry analysis follow closely the ground simulation qualitative results. The pre-flight testing and simulations program for the SAC-A spacecraft contributed to the improvements in the GPS simulations and receivers technology and operations. The successful flight of SAC-A will contribute significantly to the next Argentine spacecraft project, SAC-C, and future spacecraft carrying GPS sensors.

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